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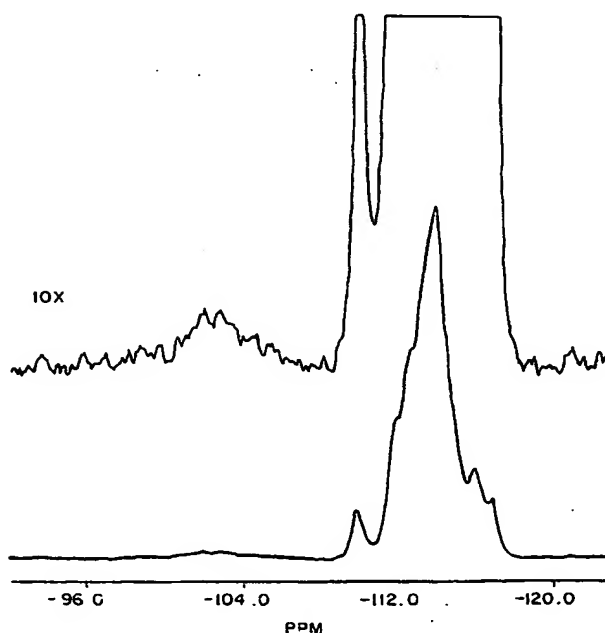
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54 **Membrane formed of crystalline molecular sieve material.**

57 A synthetic, non-composited microporous membrane comprises a continuous array of crystalline molecular sieve material, and may be made by crystallizing a thin layer of the molecular sieve material on to a non-porous forming surface from which it is subsequently removed. The membrane may be used as a catalyst or as a separator for liquid or gaseous mixtures.

FIG. 1



The invention relates to membranes having molecular sieve properties and/or catalytic activity and to a process for manufacturing them.

Membrane separation technology is a rapidly expanding field. Organic and inorganic materials have been used as membranes in a variety of separation processes, such as microfiltration, ultrafiltration, dialysis, electrodialysis, reverse osmosis and gas permeation. Most membranes have been made from organic polymers with pore sizes ranging from 10 to 1000 angstroms. Membranes have also been made from inorganic materials such as ceramics, metals, clay and glasses.

Zeolites have been used as adsorptive separation agents for gases or liquids or as catalysts, and have usually been used in the form of granules or pellets often composited with a binder such as clay or alumina.

Zeolites have been used as components in composite membranes in which the membrane material contains a second component with distinctly different chemical composition, physical properties, chemical properties and morphology. As a result of the presence of different phases, the separation properties of composite membranes are determined by the individual properties of the different phases and of the phase boundaries. (Demertzes et al. J. Chem. Soc., Faraday Trans. 1, 82, 3647 (1986)). Examples of such non-zeolitic phases are polymeric materials and inorganic materials such as glasses, silica or alumina.

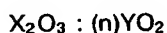
Composite membranes or filters of materials such as paper and polymers which may contain dispersed particles of zeolites have been described, for example, in US-A-3,266,973, 3,791,969, 4,012,206, 4,735,193 and 4,740,219 and in EP-A-254,758. US-A-4,699,892 describes a composite membrane having a film of zeolite from 10 to several hundred angstroms in thickness in the pores of a metal, inorganic or polymeric membrane support. Non-composited inorganic membranes are described, for example, in US-A-3,392,103, 3,499,537, 3,628,669 and 3,791,969.

US-A-3,392,103 describes membranes made from hydrous metal oxide ceramics such as aluminum oxide. US-A-3,499,537 discloses membranes of pressed and sintered aluminum vanadate powder. US-A-3,628,669 discloses silica membranes made by leaching thin inorganic glass films. US-A-3,791,969 describes membranes of flocculated sodium exfoliated vermiculite.

Non-composited membranes described in US-A-3,413,219 and 4,238,590 require some manner of supporting material. US-A-3,413,219 discloses the preparation of membranes from colloidal hydrous oxide which is formed on a permeable substrate. US-A-4,238,590 discloses silicic acid heteropolycondensates suitable for use as membranes but which are not self-supporting and are stretched over porous or net-like supporting material.

It is therefore an object of the invention to provide a pure and spatially continuous molecular sieve membrane. It is also an object to provide a material of macroscopic dimensions, composed only of a zeolitic phase, and having adequate mechanical strength to maintain its macroscopic structural integrity and capable of carrying out molecular sieve action.

The invention is a synthetic, non-composited, microporous membrane comprising a continuous array of crystalline molecular sieve materials. The molecular sieve may have a composition in terms of mole ratios of oxides as follows:



wherein X is a trivalent element of at least one member selected from the group consisting of aluminum, boron, iron and gallium. Y is a tetravalent element of at least one member selected from the group consisting of silicon, germanium and titanium; and, n is at least 2.

The crystalline materials may also be an aluminophosphate, silicoaluminophosphate, metalloaluminophosphate or metalloaluminophosphosilicate.

Also in accordance with the invention, a method is provided for preparing the microporous membrane. A reaction mixture capable of forming the crystalline molecular sieve material is prepared and the mixture is formed into a thin, uncomposited, cohesive, continuous membrane, dried and calcined.

A method is also provided for using the membrane for the separation of the components of a gaseous or liquid mixture having at least two components. The mixture is contacted with an upstream face of the membrane under separation conditions such that at least one component of the mixture has a greater steady state permeability through the membrane than at least one of the remaining component(s) of the mixture. After contact of the mixture with the membrane and passage through the membrane, the component with the greater permeability is collected on the downstream side of the membrane.

A method is also provided for using the membrane as a catalyst. The membrane is rendered catalytically active and a feedstock is passed through the upstream face of the membrane under catalytic conditions. For cases where all or at least one of the reaction products have higher permeability than the reactant(s), they will emerge from the downstream side of the membrane. In equilibrium limited reactions,

this will lead to higher single-pass conversion of the reactant(s) than normally observed and allowed by thermodynamic equilibrium constraints. At least one or all of the reaction products are collected on the downstream side of the membrane. Other advantages can be realized, for example, when one or all of the products inhibit or poison the desired reaction, or when they would undergo undesired secondary reactions.

The microporous zeolitic membranes of the invention advantageously have unique molecular sieve and/or catalytic properties due to the well defined pore structure of zeolites. The membranes have the advantages of having different properties from traditionally used granular form zeolites, and from composited membranes which include zeolites. These different properties result from the sheet-like structure of the membranes and the composition of pure zeolite in the membrane.

Zeolites include a wide variety of positive ion-containing crystalline aluminosilicates. These aluminosilicates can be described as a rigid three-dimensional framework of  $\text{SiO}_4$  and  $\text{AlO}_4$  in which the tetrahedra are cross-linked by the sharing of oxygen atoms whereby the ratio of the total aluminum and silicon atoms to oxygen atoms is 1:2. The electrovalence of the tetrahedra containing aluminum is balanced by the inclusion in the crystal of the cation, for example an alkali metal or an alkaline earth metal cation.

One type of cation may be exchanged either entirely or partially with another type of cation utilizing ion exchange techniques in a conventional manner. By means of such cation exchange, it has been possible to vary the properties of a given aluminosilicate by suitable selection of the cation. The spaces between the tetrahedra are occupied by molecules of water prior to dehydration.

Zeolites typically have uniform pore diameters of about 0.3 to about 1.0 nm. The chemical composition of zeolites can vary widely and they typically consist of  $\text{SiO}_2$  in which some of the silicon atoms may be replaced by tetravalent ions such as Ti or Ge, by trivalent ions such as Al, B, Ga, Fe, or by bivalent ions such as Be, or by a combination of any of the aforementioned ions. When there is substitution by bivalent or trivalent ions, cations such as Na, K, Ca,  $\text{NH}_4$  or H are also present.

Representative examples of zeolites are small pore zeolites such as NaA, CaA, Erionite, ZK-4 and ZK-5; medium pore zeolites such as ZSM-5, ZSM-11, ZSM-22, ZSM-23, ZSM-35, ZSM-38, ZSM-48, ZSM-12, zeolite beta; and large pore zeolites such as zeolite L, ZSM-4 (omega), NaX, NaY, CaY, REY, US-Y, ZSM-20 and mordenite.

The silicon/aluminum atomic ratio of a given zeolite is often variable. For example, zeolite X can be synthesized with silicon/aluminum atomic ratios of from 1 to 1.5; zeolite Y, from 1.5 to about 3. In some zeolites, the upper limit of the silicon/aluminum atomic ratio is unbounded. ZSM-5 is one such example wherein the silicon/aluminum atomic ratio is at least 12: US-A-3,941,871 discloses a porous crystalline silicate made from a reaction mixture containing no deliberately added aluminum and exhibiting the x-ray diffraction pattern characteristic of ZSM-5 type zeolites. US-A-4,061,724, 4,073,865 and 4,104,294 describe crystalline silicas of varying aluminum and metal content. These zeolites can consist essentially of silica, containing only traces or no detectable amounts of aluminum.

Another class of molecular sieves consists of  $\text{AlO}_2 \cdot \text{PO}_2$  units ( $\text{AlPO}_4$ ) whose Al or P constituents optionally may be substituted by other elements such as Si (the silicoaluminophosphates or SAPOs), or metals (the metalloaluminophosphates or MeAPOs) or combinations therefore (the metalloaluminophosphosilicates or MeAPSOs). As with aluminosilicates, the  $\text{AlPO}_4$ s, SAPOs, MeAPOs and MeAPSOs are crystalline and have ordered pore structures which accept certain molecules while rejecting others and they are often considered to be zeolitic materials.

The crystalline silicoaluminophosphates useful for the membranes of the invention have molecular sieve framework which may exhibit ion-exchange properties and may be converted to material having intrinsic catalytic activity.

Aluminum phosphates having essentially electroneutral lattices are taught in US-A-4,310,440 and 4,385,994, whilst US-A-3,801,704 discloses an aluminum phosphate treated to impart acidity.

Silicoaluminophosphates of various structures are disclosed in US-A-4,440,871. Aluminosilicates containing phosphorus, i.e. silicoaluminophosphates of particular structures, are disclosed in US-A-3,355,246 (ZK-21) and 3,791,964 (ZK-22). Other disclosures of silicoaluminophosphates and their synthesis occur in US-A-4,673,559 (two-phase synthesis method); 4,623,527 (MCM-10); 4,639,358 (MCM-1); 4,647,442 (MCM-2); 4,664,897 (MCM-4); 4,638,357 (MCM-5); and 4,632,811 (MCM-3).

A method for synthesizing crystalline metalloaluminophosphates (MeAPOs) is disclosed in US-A-4,713,227 and an antimonophosphoaluminate and the method for its synthesis are disclosed in US-A-4,619,818. US-A-4,567,029 discloses metalloaluminophosphates, and titaniumaluminophosphate and the method for its synthesis are disclosed in US-A-4,500,651. US-A-4,880,611 discloses compositions comprising crystals having a framework topology, after heating at  $110^\circ\text{C}$  or higher, giving an x-ray diffraction pattern indicating pore windows formed by 18 tetrahedral members of about 1.2 to 1.3 nm in diameter.

The membranes of the invention consist of molecular sieve material; as contrasted with prior art

composite membranes which contain various amounts of molecular sieve material composited with other materials. The membrane may contain a single zeolite or mixture of zeolites. The membrane can be monocrystalline or polycrystalline, i.e. may consist of a single crystal or of a continuous intergrowth of many crystals.

The membrane can be produced by synthesis of molecular sieve material under hydrothermal conditions on a non-porous forming surface, such as a polymer, a metal or glass. Suitable polymer surfaces are, for example, fluorocarbon polymers such as tetrafluoroethylene and fluorinated ethylene-propylene polymers. Suitable metal surfaces are, for example, silver, nickel, aluminum and stainless steel. A thin layer of metal on glass or an organic polymer or other material may be used as the forming surface. A thick layer of a polymer film on glass or other material may also be used as the forming surface. The forming surface may have various configurations. For example, the surface may be flat, curved, a hollow cylinder or honeycomb-shaped. Both amorphous materials and monocrystalline surfaces can be used as forming surface for crystal growth. The synthesis can also be achieved by mechanical compression of a powder form zeolite, followed by chemical treatment.

In forming the membranes of the invention, a non-porous surface is contacted with a reaction mixture capable of forming the desired crystalline material under crystallization conditions. After a period of time under suitable conditions, a cohesive membrane of crystallized material forms on the non-porous surface. The thickness of the membrane may vary from about 0.1 to about 400 micrometers depending upon the length of time the surface is contacted with the reaction mixture and the amount of mixture provided. Other means such as varying the temperature or the ratio of reaction mixture to forming surface area are also effective in adjusting the membrane thickness to a desired dimension.

The time of contacting of the surface with the reaction mixture may be from about 0.5 hrs to about 1000 hrs, preferably from about 1 hr to about 100 hrs; at a temperature of from about 50°C to about 250°C; preferably from about 110°C to about 200°C; and at a pressure from about 1 bar to about 100 bar, preferably from about 1 bar to about 15 bar. After the desired period of time the surface coated with crystalline material is removed from contact with the reaction mixture, washed with distilled water and allowed to dry.

The reaction mixture advantageously has the following composition in terms of moles per mole  $\text{YO}_2$ :

		Most	
	<u>Broad</u>	<u>Preferred</u>	<u>Preferred</u>
$\text{H}_2\text{O}/\text{YO}_2$	5 to 500	20 to 500	40 to 500
$\text{X}_2\text{O}_3/\text{YO}_2$	0 to 0.2	0 to 0.014	0 to 0.010
$\text{OH}^-/\text{YO}_2$	0 to 2	0.02 to 0.15	0.02 to 0.15

The layer of crystalline material may be removed from the non-porous surface by various means, depending upon the material chosen for the surface. The layer may be separated from polymeric surfaces, for example, by mechanical means such as careful scraping or peeling. Removal from metal surfaces may be accomplished with the use of solvents such as acetone, or by dissolving the metal with acid such as aqueous hydrochloric or nitric acid. With a support consisting of metal or metallized material such as aluminum on glass or teflon, treatment with an aqueous mineral acid can be employed.

There results a permeable membrane, comprising a self-supporting web of in-situ-crystallized zeolite (or other molecular sieve), of which the pores providing for permeation are those of zeolites. Although self-supporting, the membrane may, for added mechanical strength, be disposed in use upon a suitably firm support having a porosity sufficiently gross in relation to that of the zeolite to be devoid of influence upon the permeability of the membrane.

The membrane material may also be calcined before or after removal from the substrate, for example in an inert atmosphere or in air at from about 200°C to about 700°C for about 1 hr to about 50 hrs.

The membrane may also be treated to adjust its catalytic properties before or after removal from the surface, for example by steaming and/or ion exchange. Low or zero catalytic activity can be obtained by incorporating alkali or alkaline earth cations into the membrane.

Catalytic activity can be increased by methods known in the art such as by increasing the aluminum content or by introducing a hydrogenation-dehydrogenation function into the membrane.

The original ions, i.e. cations or anions, of the synthesized membrane can be replaced in accordance

with techniques well known in the art, at least in part, by ion exchange with other cations or anions. Preferred replacing cations include metal ions, hydrogen ions, hydrogen precursor, e.g. ammonium ions and mixtures thereof. Particularly preferred cations include hydrogen, rare earth metals and metals of Groups IIA, IIIA, IVA, IB, IIB, IIIB, IVB, VIB and VIII of the Periodic Table of the Elements.

5 Typical ion exchange technique would be to contact the synthesized membrane with a salt of the desired replacing ion or ions. Examples of such salts of cations include the halides, e.g., chlorides, nitrates and sulfates.

Cations may be incorporated into the membrane to neutralize acid sites or to adjust the diffusion properties; preferred cations to be incorporated for these purposes include metals of Groups IA and IIA of  
10 the Periodic Table of the Elements, for example sodium, potassium, magnesium, barium, lithium, strontium, rubidium and cesium.

The diffusive properties of the membrane such as permeation rate and selectivity, depend on the geometric properties, particularly the thickness, and the particular zeolite that constitutes the membrane. A given membrane can be further modified by subsequent treatment that changes the diffusion properties.  
15 Examples of such treatments are: deposition of coke or organic compounds, such as pyridine or other carbonaceous material, at the exterior or interior of the zeolite pores, deposition of silica or silicon compounds via treatment with  $\text{SiCl}_4$  or  $\text{Si}(\text{OR})_4$  followed by calcination, treatment with phosphorus compounds, incorporation of metal salts or oxides, such as of Mg, Mo, W, Sb, or other oxides such as silicon dioxide, or ion exchange, e.g., with K, Rb, Cs, or Ag.

20 It is also contemplated that a metal function can be incorporated into the membrane, such as Pd, Pt, Ru, Mo, W, Ni, Fe, Ag, etc. These metal-containing membranes may have essentially no acid activity, or they may have substantial acid activity to provide for dual-functional catalysis. The catalytic activity of the membrane can be adjusted from essentially zero to high activity, depending on the particular use thereof.

The membranes can be used for separation of gaseous or liquid mixtures or catalytic applications which  
25 combine chemical conversion of the reactant with in situ separation of the products.

A variety of gaseous or liquid mixtures may be separated using the membrane. Examples of mixtures advantageously separated are oxygen and nitrogen, hydrogen and carbon monoxide, linear and branched paraffins, hydrogen and methane, p-xylene and m- and/or o-xylene.

Further useful separations which can be carried out with the membranes described herein include:  
30 removal of waxy components from distillate and lube oil fractions and of linear and slightly branched paraffins from aromatics or aromatics-containing mixtures such as reformat; removal of organics from aqueous streams, in which high silica ( $\text{SiO}_2/\text{Al}_2\text{O}_3 > 100$ ) microporous materials are particularly useful; removal of ethanol from fermentation mixtures used to produce beer or wine; removal of harmful organic contaminants from ground water or waste streams; and removal of paraffins from aromatics using a high  
35 silica zeolite membrane, and aromatics from paraffins, using low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  zeolite membrane in the alkali-exchanged form.

When separation of the components of a gaseous or liquid mixture is to be accomplished, a low or zero activity zeolitic membrane is preferably used. Siliceous zeolites of low or zero activity contain only trace amounts of two- or three-valent metals or none at all; when they contain a substantial amount of such  
40 metals, their catalytic activity can be reduced to the desired low level by cation exchange with alkali or alkaline earth cations, by thermal or steam treatment, by treatment with phosphorus compounds and steaming, or by replacement of the three-valent elements, e.g. Al, by four-valent elements, e.g. Si, by treatment with hexafluorosilicate,  $\text{SiCl}_4$ , etc. Aluminophosphate molecular sieves also have low, if any, catalytic activity.

45 Catalytic applications can combine chemical conversion of one or more reactants with in situ separation. Such separation may involve, for example, the separation of one or all of the products from the reactant(s).

For use in a catalytic process, (i) a catalytically inactive membrane may be combined with an active catalyst, or (ii) the membrane itself may be catalytically active. As an example of the first case (i), a Pt on  $\text{Al}_2\text{O}_3$  catalyst is contained in a tubular reactor whose walls consist at least partly of a catalytically inactive  
50 zeolitic membrane chosen to selectively permeate hydrogen.

Dehydrogenation of alkanes is an example of a catalytic process which may be accomplished by passing an alkane feed through the tubular reactor; the effluent contains alkene in greater than equilibrium concentration. In this way, for example, propane may be converted to propylene. In the second case (ii), the zeolitic membrane possesses catalytic activity, either acid activity, or metal activity, or both. The acid  
55 activity of siliceous zeolites can be adjusted by the amount of three-valent substituents especially aluminum, but the degree of cation exchange from salt form to hydrogen form or by thermal or steam treatment. The acid activity of  $\text{AlPO}_4$ -type zeolites can be increased by incorporation of activating agents such as silica. An example utilizing the acid activity of the membrane is the dealkylation of ethylbenzene to

benzene and ethylene. Utilizing the higher permeation rate of ethylene alone or of ethylene and benzene, a higher degree of dealkylation in greater selectivity is obtained.

The crystalline membranes of the present invention are readily convertible to catalytically active material for a variety of organic, e.g. hydrocarbon, compound conversion processes. Such conversion processes include, as non-limiting examples, cracking hydrocarbons with reaction conditions including a temperature of from about 300 to about 700 °C, a pressure of from about 0.1 bar to about 30 bar and a weight hourly space velocity of from about 0.1<sup>-1</sup> to about 20 hr<sup>-1</sup>; dehydrogenating hydrocarbon compounds with reaction conditions including a temperature of from about 300 to about 700 °C, a pressure of from about 0.1 bar to about 10 bar and a weight hourly space velocity of from about 0.1 to about 20, converting paraffins to aromatics with reaction conditions including a temperature of from about 100 to about 700 °C, a pressure of from about 0.1 bar to about 60 bar, a weight hourly space velocity of from about 0.5 to about 400 and a hydrogen/hydrocarbon mole ratio of from about 0 to about 20; converting olefins to aromatics, e.g. benzene, toluene and xylenes, with reaction conditions including a temperature of from about 100 to about 700 °C, a pressure of from about 0.1 to about 60 bar, a weight hourly space velocity of from about 0.5 to about 400 and a hydrogen/hydrocarbon mole ratio of from about 0 to about 20; converting alcohols, e.g. methanol, or ethers, e.g. dimethylether, or mixtures thereof to hydrocarbons including olefins and/or aromatics with reaction conditions including a temperature of from about 275 to about 600 °C, a pressure of from about 0.5 to about 50 bar and a liquid hourly space velocity of from about 0.5 to about 100; isomerizing xylene feedstock components with reaction conditions including a temperature of from about 230 to about 510 °C, a pressure of from about 3 to about 35 bar, a weight hourly space velocity of from about 0.1 to about 200 and a hydrogen/hydrocarbon mole ratio of from about 0 to about 100; disproportionating toluene with reaction conditions including a temperature of from about 200 to about 760 °C, a pressure of from about 1 to about 60 bar and a weight hourly space velocity of from about 0.08 to about 20; alkylating aromatic hydrocarbons, e.g. benzene and alkylbenzenes in the presence of an alkylating agent, e.g. olefins, formaldehyde, alkyl halides and alcohols, with reaction conditions including a temperature of from about 250 to about 500 °C, a pressure of from about 1 to about 200 bar, a weight hourly space velocity of from about 2 to about 2000 and an aromatic hydrocarbon/alkylating agent mole ratio of from about 1/1 to about 20/1; and transalkylating aromatic hydrocarbons in the presence of polyalkylaromatic hydrocarbons with reaction conditions including a temperature of from about 340 to about 500 °C, a pressure of from about 1 to about 200 bar, a weight hourly space velocity of from about 10 to about 1000 and an aromatic hydrocarbon/polyalkylaromatic hydrocarbon mole ratio of from about 1/1 to about 16/1.

In general, therefore, catalytic conversion conditions over a catalyst comprising the membrane in active form include a temperature of from about 100 to about 760 °C, a pressure of from about 0.1 to about 200, a weight hourly space velocity of from about 0.08 hr<sup>-1</sup> to about 2000 hr<sup>-1</sup> and a hydrogen/organic, e.g. hydrocarbon compound of from 0 to about 100.

In order to illustrate the nature of the invention and the manner of practising same, the following examples are presented. In the drawings:

Figure 1 is Si-NMR spectrum of a crystalline membrane.

Figure 2a shows a membrane surface which was exposed to a non-porous substrate during crystallization.

Figure 2b shows a membrane surface which was exposed to a synthesis mixture.

Figure 2c shows crystal intergrowth on the surface of a large single crystal.

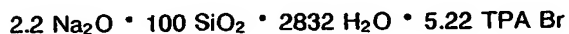
Figure 2d is a higher magnification of the view of Figure 2c.

Figure 3 illustrates a membrane affixed in a Wicke-Kallenbach cell.

#### EXAMPLE 1

The procedure outlined by Hayhurst and Lee (Proceedings of the 7th International Zeolite Conference, Murakami, Y., Iijima, A., Ward, I.W. Ed., p. 113, Elsevier, Tokyo, 1986) was followed.

Tetrapropylammonium bromide (Aldrich), 3.475 gm, was dissolved in 50.0 gm distilled water by stirring in a polyethylene container. 0.90 gm of 50% sodium hydroxide solution (Baker, reagent grade) was added. The resulting solution was subsequently diluted with 34.6 gm distilled water. 37.55 gm of Ludox AS-40 aqueous colloidal silica (DuPont) was slowly added with continuous stirring. About 40 ml of the suspension was poured into a 45 ml polytetrafluoroethylene (Teflon) lined autoclave (Parr Model 4744). The molar composition was:



A polytetrafluoroethylene slab (80 mm X 25 mm X 2.5 mm) was immersed in the solution and placed vertically along the axis of the cylindrical vessel. The autoclave was sealed and placed in a convection oven, which was preheated at 180° C.

In a second autoclave, a vycor frit, approximately 1.5 cm in diameter, already mounted inside a pyrex tube (Corning Glass), was immersed in the synthesis solution.

The autoclaves were removed from the oven after 9 days and quenched with water. The Teflon slab was recovered, washed with distilled water and dried at room temperature. The slab and the vycor frit with surrounding pyrex tube were observed to be covered with a uniform layer of crystallized material.

The layer of crystalline material was removed from the Teflon surfaces by carefully scraping with a spatula. No solid particles were found suspended in the remaining solution or settled on the bottom of the container.

The resulting membranous material was calcined in nitrogen at 560° C and in air at 600° C to decompose and burn off the organic template. No cracks generated by the calcination process were observed.

Segments of the zeolite membrane greater than 1cm<sup>2</sup> were selected for characterization by electron microscopy, x-ray diffraction, Silicon-NMR and hexane sorption. The membrane was crushed to powder form for x-ray and Silicon-NMR tests. It was introduced uncrushed into the sorption apparatus for hexane sorption measurements.

#### X-ray Diffraction, Si-NMR and Hexane Sorption

The x-ray diffraction pattern was that of pure ZSM-5. The Si-NMR spectrum, Figure 1, showed silanols as the only non-ZSM-5 framework silicons. Spectra with 30 and 300s relaxation delays were obtained to be certain no dense phases were present. Silanols, whose identity was established by crosspolarization, are seen as a broad peak at about -103 ppm. Their concentration is about 1.5 SiOH/unit cell or about 1/3 what is normally present in a high silica ZSM-5 made from TPABr. The hexane sorption capacity, measured at 90° C and 110.8 torr hexane partial pressure, was found to be 112.0 mg/gm of zeolite, i.e. slightly higher than the sorption capacity of standard small ZSM-5 crystals.

#### Electron Microscopy

Figure 2 shows the distinct morphologies of the two membrane surfaces. Figure 2a corresponds to the membrane surface exposed to the teflon support. Figure 2b corresponds to the surface exposed to the synthesis mixture. Although the teflon side surface consists of a layer of apparently loosely held crystals of less than 0.1 micrometer size, the solution surface consists of a continuous array of densely packed and intergrown (twinned) crystals, 10 to 100 micrometers in size. The intergrowth is better shown on the surface of a large single crystal (Figure 2c). The surface of the same crystal at even higher magnification is shown in Figure 2d. This is partly coated with small particles, which may or may not have the ZSM-5 microstructure.

The thickness of the membrane was estimated to be about 250 micrometers.

#### Permeability Measurements

Permeability properties of the membrane were determined in a Wicke-Kallenbach cell, operated in the steady state mode (Figure 3). Both sides of the membrane were glued with epoxy resin onto the perimeter of two Pyrex tubes, 1 cm in diameter. The membrane material extending beyond the external surface of the tubes was destroyed. A thick layer of epoxy resin was applied to the external surface of the junction to provide extra mechanical support and eliminate the possibility of gas leaks. The temperature limit of the epoxy resin used was 120° C. The Wicke-Kallenbach cell was incorporated in a standard flow apparatus, capable of operating at atmospheric or subatmospheric pressure. The permeability coefficient (P) of a component across the membrane is defined as the ratio of the flux-unit area to the external concentration gradient of the component. It is related to the Wicke-Kallenbach diffusion coefficient (D<sub>wk</sub>) by the expression:  $P = K_h \cdot D_{wk}$  (Matson et al., Chem. Eng. Sci., 38, 503 (1983)) where  $K_h$  is the Henry's Law constant. This expression is only valid in the Henry's Law regime. It reflects the fact that the true but not directly measurable driving force for diffusion, which is the intracrystalline concentration gradient, differs from the external concentration gradient due to the equilibrium partitioning of the adsorbate established

between the membrane surface and the external gas phase (Koresh, et al., J. Chem. Soc, Faraday Trans. 1, 82, 2057 (1986)). For a bicomponent feed stream, the selectivity is defined as the permeability ratio. Except for a few data collected at 23°C, permeabilities were measured at 49°C and 1 bar total pressure on both sides of the membrane. The flow rate of the feed side was 249 cc/min and that of the permeate side was 14.1 cc/min. Helium was used as a carrier gas of the permeate.

Permeability coefficients and selectivities were calculated for three bicomponent gas mixtures:

Feed	Composition (mole %)
1	21% O <sub>2</sub> /79% N <sub>2</sub>
2	49.4% H <sub>2</sub> /50.6% CO
3	9.5% n-C <sub>6</sub> /16.6% 2,2-DMB/helium balance (normal hexane/2,2-dimethylbutane)

The following permeability coefficients and selectivities were determined:

Feed	Temp (°C)	Perm. Comp. (mole %)	P1 (cm <sup>2</sup> /s)	P2 (cm <sup>2</sup> /s)	Selectivity
1	49	.46±.01/1.62±.04	1.31·10 <sup>-4</sup>	1.22·10 <sup>-4</sup>	1.07±.05
2	23	2.12±.05/1.36±.05	2.63·10 <sup>-4</sup>	1.63·10 <sup>-4</sup>	1.62±.04
2	49	2.20±.02/1.48±.01	2.59·10 <sup>-4</sup>	1.92·10 <sup>-4</sup>	1.54±.01
3	49	.335±.002/.0354±.0007	1.96·10 <sup>-4</sup>	1.14·10 <sup>-5</sup>	17.2±1.5

The composition of the recovery stream differs from the composition of the feed stream, the membrane separating O<sub>2</sub> and N<sub>2</sub>, H<sub>2</sub> and CO, and hexane and 2,2-dimethylbutane. This shows that the zeolitic membrane can discriminate between permeates at the molecular level. The selectivities observed for the H<sub>2</sub>/CO and hexane/2,2-dimethylbutane feeds strongly suggest that most of the transport across the membrane takes place in the shape selective pores of the ZSM-5 lattice.

#### EXAMPLES 2-5

The same synthesis mixture and conditions as described in Example 1 were used except that the crystallization time was varied.

The thickness of the membranes formed was found to be a function of the crystallization time as shown in Table 1. It is apparent that long crystallization times lead to membranes of greater thickness.

TABLE 1

Example	Crystallization Time Days	Membrane Thickness Micrometers
2	0.3	20
3	1	150
4	2	210
5	4	230



## EXAMPLE 6

Example 1 was repeated except that a 25x25 mm flat silver plate was used instead of the teflon plate. A ZSM-5 membrane formed on the surface of the silver plate.

The silver plate was washed with water and dried at room temperature. The crystallized zeolite membrane could be readily removed from the support plate by wetting the surface with acetone at room temperature.

## EXAMPLE 7

Example 1 was repeated using a 25x25 mm flat nickel plate. At the end of the crystallization period, the nickel plate was found to be coated with a thin ZSM-5 zeolite membrane.

## EXAMPLE 8

Example 1 was repeated using a flat plate made of No. 316 stainless steel. Zeolite crystallization again occurred on the surface of the stainless steel plate in the form of a thin membrane.

## EXAMPLE 9

0.78 gm  $\text{NaAlO}_2$  and 1.12 gm NaOH pellets were dissolved in 497.7 gm deionized water. 7.98 gm tetrapropylammonium bromide salt was dissolved in the resulting solution, followed by 60.0 gm colloidal sol (30%  $\text{SiO}_2$ ). The final solution was stirred vigorously for two minutes to produce a homogeneous solution.

The resultant hydrogel is manifested by the mole ratios:

$\text{H}_2\text{O}/\text{SiO}_2$	100
$\text{Al}_2\text{O}_3/\text{SiO}_2$	0.01
$\text{OH}^-/\text{SiO}_2$	0.10
$\text{Na}^+/\text{SiO}_2$	0.12
$\text{TPA}^+/\text{SiO}_2$	0.10

A quantity of the hydrogel was transferred to a one liter stainless steel autoclave which held a vertically-mounted teflon strip. The autoclave was sealed and immediately heated, for 3 days at  $180^\circ\text{C}$ , without stirring, before quenching to room temperature to terminate the crystallization.

The autoclave was opened and the teflon strip removed from the remaining liquid. Crystalline product had deposited upon the teflon surface, and a crystalline zeolite membrane was physically removed intact from the teflon surface.

## EXAMPLE 10

Forty-five milliliters of the hydrogel prepared in Example 9 was transferred to a 65 ml stainless steel autoclave. A teflon strip was mounted vertically within the autoclave, which was then capped, sealed, and placed into a convection oven set at  $180^\circ\text{C}$ . The autoclave remained in the convection oven at  $180^\circ\text{C}$  (at static conditions) for 4 days before removal to cool to room temperature.

When the autoclave was opened, it was observed that uniform crystalline deposit has taken place on the surface of the teflon strip. A crystalline zeolite membrane was removed intact from the teflon surface.

## EXAMPLE 11

A solution was prepared as described in Example 9 but with the following composition:

	$\text{H}_2\text{O}/\text{SiO}_2$	29
	$\text{Al}_2\text{O}_3/\text{SiO}_2$	0.0025
	$\text{OH}^-/\text{SiO}_2$	0.02
5	$\text{Na}^+/\text{SiO}_2$	0.05
	$\text{TPA}^+/\text{SiO}_2$	0.05

10 The hydrogel was transferred to a 45 ml teflon-lined autoclave, which held a vertically-mounted teflon slab.

The autoclave was sealed and placed in a 180°C oven for 3 days. The autoclave was quenched, opened and the teflon slab was removed. It was observed that crystalline product in the form of a uniformly thick layer had deposited upon the teflon surface. This crystalline zeolite membrane was physically removed intact from the teflon surface.

15 The Examples which follow employ a membrane reactor consisting of a cylindrical tube 2 cm in diameter and 30 cm long having walls composed of a 12 micrometer thick membrane having the structure of ZSM-5 supported by a porous alumina support, the membrane being on the interior of the tube. This tube is mounted concentrically inside a metal tube of 3 cm inside diameter creating an inter-tube annulus with a width of about 0.5 cm. The inside membrane tube and the outer annulus are fitted with separate feed and exit lines.

#### EXAMPLE 12

25 The membrane reactor employed has a membrane wall composed of ZSM-5 of  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio >20,000, which is essentially catalytically inactive. Forty ml of HZSM-5 with a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 70 in the form of 1/16 inch extrudates was placed inside the inner tube of the reactor. A feed stream of vaporized cumene at 350°C and 1 bar pressure was passed through the inner tube at a weight hourly space velocity of 10  $\text{hr}^{-1}$ . Propylene and benzene were withdrawn in high purity from the annular space, which was swept with a stream of nitrogen.

30 By comparison, when the 70  $\text{SiO}_2/\text{Al}_2\text{O}_3$  HZSM-5 catalyst is placed in a conventional, non-membrane reactor tube, cumene is converted under the above conditions to benzene and di- and triisopropylbenzene with only traces of propylene.

#### 35 EXAMPLE 13

The membrane reactor employed had a membrane wall composed of ZSM-5 with a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 700, and was loaded with a mixture of 10 gm molybdenum oxide and 30 gm of quartz particles. Cyclohexane is passed through the tube at a temperature of 200°C and pressure of 25 bar at a WHSV of 2  $\text{hr}^{-1}$ . Oxygen is passed through the annular tube at a rate of 40 ml pr min. The reactor effluent contains cyclohexanone and cyclohexanol in high selectivity with only small amounts of  $\text{CO}_2$ . In a conventional non-membrane reactor where the oxygen is cofed with the cyclohexane feed, the selectivity to the desired product is considerably lower.

#### 45 EXAMPLE 14

The membrane reactor employed had a membrane wall composed of ZSM-5 with a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 3000 impregnated with a solution of vanadium nitrate in an amount to give 0.5 wt% vanadium metal based on total zeolite, and treated with an air stream at 500°C for 2 hours, to deposit a thin layer of vanadium (V) oxide on the inner surface. A mixture of isobutane and n-butane containing 40% isobutane is passed at 220°C and 25 bar pressure through the inner tube at WHSV of 2  $\text{hr}^{-1}$ , based on the weight of the metal oxide. Air at the same temperature and 28 bar pressure is passed through the annular space. The products collected from the inner tube product stream contain tertiary-butyl alcohol, acetone and trace quantities of  $\text{CO}_2$ . n-Butane is essentially unreacted and is recovered in pure form by simple distillation from the oxygenated products.

#### EXAMPLE 15

The membrane employed had a membrane wall composed of the potassium form of zeolite ZSM-5 with  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 220. The inner surface of the tube is impregnated with a solution of chloroplatinic acid in an amount to give 0.001 wt% platinum based on total zeolite, and treated in a hydrogen stream at  $500^\circ\text{C}$  for 6 hours, to deposit platinum metal on the inner surface of the membrane tube. Isobutane preheated to  $560^\circ\text{C}$  is passed through the tube at 1 bar pressure and converted to isobutene and hydrogen. The latter is withdrawn in high purity from the annular reactor tube.

#### EXAMPLE 16

Into the membrane reactor of Example 12 is placed a mixture of 10 gm of 0.6% Pt on alumina and 20 gm alumina. A stream of isoprene containing 2% of the undesirable linear isomer, 1,3-pentadiene, is passed through the outer annular reactor at  $100^\circ\text{C}$  at a flow rate of 40 gm per hour. Hydrogen in a mole ratio of 0.1 mole hydrogen per mole of hydrocarbon is passed through both the inner and outer tubes. The effluent consists of isoprene containing less than 1% of pentadiene and small amounts of n-pentane.

#### EXAMPLE 17

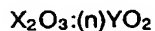
The inner tube of the membrane reactor of Example 12 is charged with 40 gm of small crystal (less than 0.1 micrometer) HZSM-5 with a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  of 70. A stream of trimethylbenzene and  $\text{H}_2$  with a  $\text{H}_2/\text{HC}$  mole ratio of 2 is conducted at  $450^\circ\text{C}$  through the inner tube at a pressure of 20 bar and a WHSV of  $2\text{ hr}^{-1}$ . A stream of toluene and  $\text{H}_2$  in a  $\text{H}_2/\text{HC}$  mole ratio of 2,  $450^\circ\text{C}$ , 20 bar pressure and a WHSV of  $1.5\text{ hr}^{-1}$  is conducted through the outer annular reactor space. The effluent from the outer reactor contains a mixture of toluene and xylenes containing the desired p-isomer in amounts considerably higher than the equilibrium concentration of 24%.

#### EXAMPLE 18

The inner tube of the membrane reactor of Example 12 is charged with 45 gm of dealuminized H-mordenite with a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 15. A stream of trimethylbenzene and hydrogen with a  $\text{H}_2/\text{HC}$  mole ratio of 2 is conducted through the tube at  $330^\circ\text{C}$  at a WHSV of  $3\text{ hr}^{-1}$  and 30 bar pressure. A stream of hydrogen (3 moles per mole trimethylbenzene) at a pressure of 10 bar is passed through the annular reactor space. The product from the inner tube reactor contains tetramethylbenzene, small amounts of penta- and hexamethylbenzene and xylenes, together with unconverted trimethylbenzene. The product from the outer annular reactor contains p-xylene, together with small amounts of m- and o-xylene and toluene.

#### Claims

1. A non-composited, microporous membrane comprising a continuous array of crystalline molecular sieve material.
2. A membrane according to claim 1 wherein the molecular sieve material has composition in terms of mole ratios of oxides as follows:



wherein X is aluminum, boron, iron and/or gallium, Y is a silicon, germanium and/or titanium, and n is at least 2.

3. A membrane according to claim 2 wherein X is aluminum and Y is silicon.
4. A membrane according to claim 2 wherein the membrane consists essentially of silica.
5. A membrane according to any of claims 2 to 4 wherein n is from 20 to 10,000.
6. A membrane according to any preceding claim wherein the molecular sieve material is a zeolite.
7. A membrane according to any of claims 1 to 5 wherein the molecular sieve material is selected from aluminophosphates, silicoaluminophosphates, metalloaluminophosphates or metal-

loaluminophosphosilicates.

8. A membrane according to any preceding claim which possesses catalytic activity and has gas or liquid separation properties.
- 5 9. A membrane according to claim 8 whereof the catalytic activity has been reduced by incorporation of alkali or alkaline earth metal.
- 10 10. A membrane according to claim 9 wherein the metal is Mg, Ca, Sr, Ba, Na, K, Li, Rb and/or Cs.
11. A membrane according to claim 8 whereof the separation properties have been adjusted by deposition of metal oxides, phosphorus compounds, silicon compounds, organic compounds, coke, alkali metal cations and/or alkaline earth metal cations.
- 15 12. A membrane according to any of claims 1 to 7 which is catalytically active.
13. A membrane according to claim 12 having a metal possessing a catalytic function incorporated therein.
14. A membrane according to claim 13 wherein the metal is Pd, Pt, Ru, Mo, W, Ni, Fe and/or Ag.
- 20 15. A membrane according to any preceding claim which is monocrystalline.
16. A membrane according to any of claims 1 to 14 which is polycrystalline.
- 25 17. A membrane according to any preceding claim which has a thickness of 0.1 to 400 micrometers.
- 30 18. A method of preparing a membrane according to claim 1 which comprises preparing a reaction mixture capable of forming a crystalline molecular sieve material, forming the mixture into a thin, cohesive, continuous membrane under crystallization conditions by allowing crystallization of the mixture in a continuous layer on a non-porous forming surface, removing the continuous layer on the forming surface from the mixture, rinsing and drying the layer and removing it from the forming surface to obtain a non-composited membrane.
- 35 19. A method according to claim 18 which further comprises calcining the removed membrane.
20. A method according to claim 18 or claim 19 which further comprises steaming the membrane at a temperature of 200 °C to 800 °C for from 1 to 50 hours.
- 40 21. A method according to any of claims 18 to 20 which further comprises ion exchanging the membrane.
22. A method according to claim 21 wherein the membrane is ion-exchanged with alkali or alkaline earth metal.
- 45 23. A method according to claim 22 wherein the metal is Mg, Ca, Sr, Ba, Na, K, Li, Rb and/or Cs.
24. A method according to any of claims 18 to 23 which further comprises incorporating a metal function into the membrane.
- 50 25. A method according to claim 24 wherein the metal function is selected from Pd, Pt, Ru, Mo, W, Ni, Fe and/or Ag.
26. A method according to any of claims 18 to 25 which further comprises depositing into the membrane a metal oxide, phosphorus compound, silicon compound, organic compound and/or coke.
- 55 27. A process for the separation of a gaseous or liquid mixture having at least two components which comprises contacting the mixture with one face of a membrane in accordance with any of claims 1 to 17 under conditions such that at least one component of the mixture has a greater steady state permeability through the membrane than one other, and recovering the component having the greater

permeability which emerges from the other face of the membrane.

28. A process according to claim 27 wherein the gaseous mixture comprises oxygen and nitrogen.

5 29. A process according to claim 27 wherein the gaseous mixture comprises hydrogen and carbon monoxide.

30. A process according to claim 27 wherein the gaseous mixture comprises hydrogen and methane.

10 31. A process according to claim 27 wherein the liquid mixture comprises a linear paraffin and a branched paraffin.

32. A process according to claim 27 wherein the liquid mixture comprises p-xylene and m- and/or o-xylene.

15 33. A process for catalytically converting a hydrocarbon feed which comprises passing said feedstock through a membrane in accordance with claim 1 under catalytic conversion conditions so that the effluent emerging from the membrane contains at least one conversion product in greater than equilibrium concentration.

20 34. A process according to claim 33 wherein a cumene feed is converted to benzene and propylene.

35. A process according to claim 33 wherein a cyclohexane feed is converted to cyclohexanone and cyclohexanol.

25 36. A process according to claim 33 wherein isobutane is converted in the presence of n-butane and air to a product containing t-butylalcohol and acetone.

37. A process according to claim 33 wherein isobutane is converted to isobutene.

30 38. A process according to claim 33 wherein 1,3-pentadiene impurity in isoprene is converted in the presence of hydrogen to n-pentane.

39. A process according to claim 33 wherein trimethylbenzene is converted to p-xylene.

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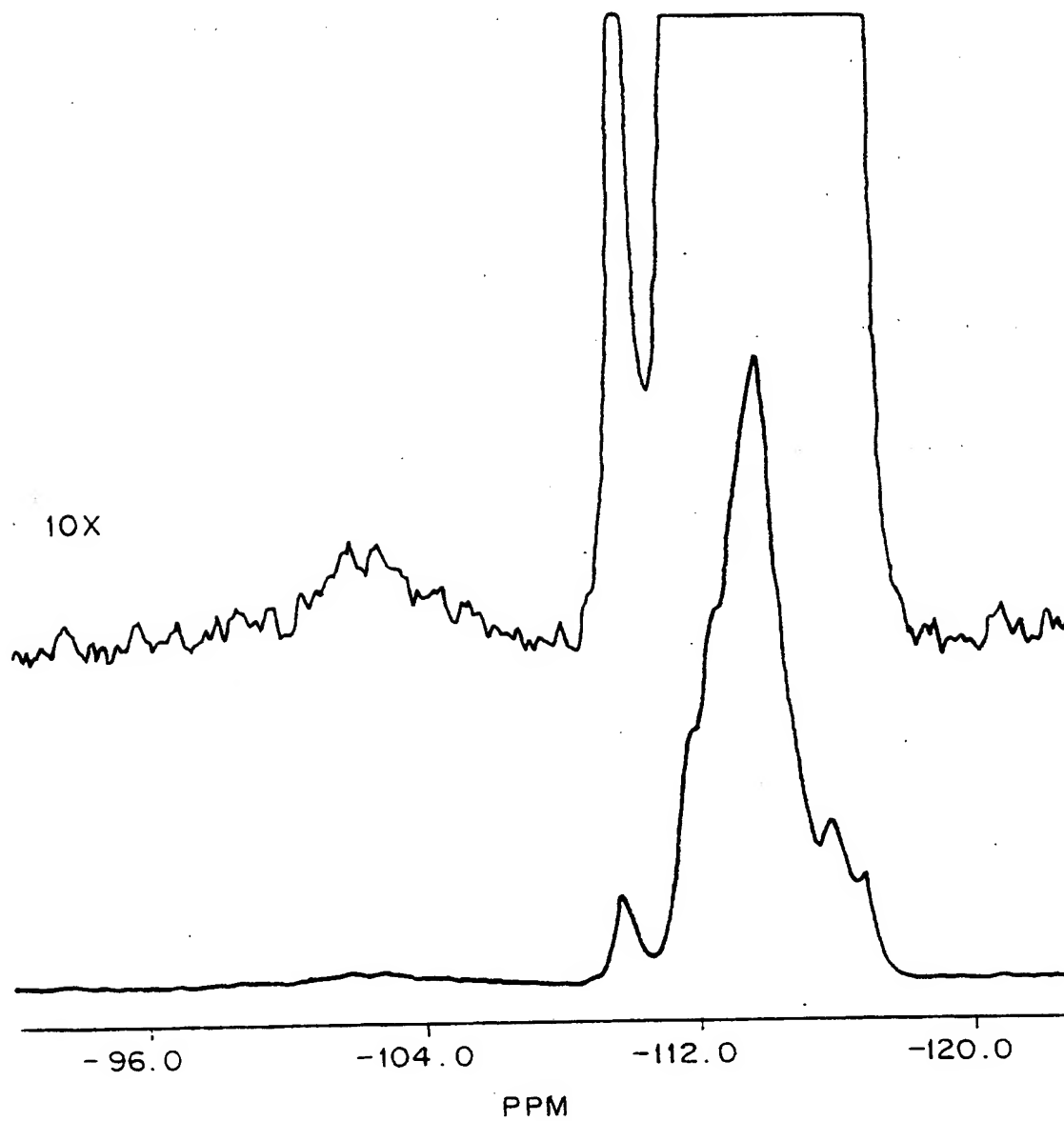
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FIG. 1



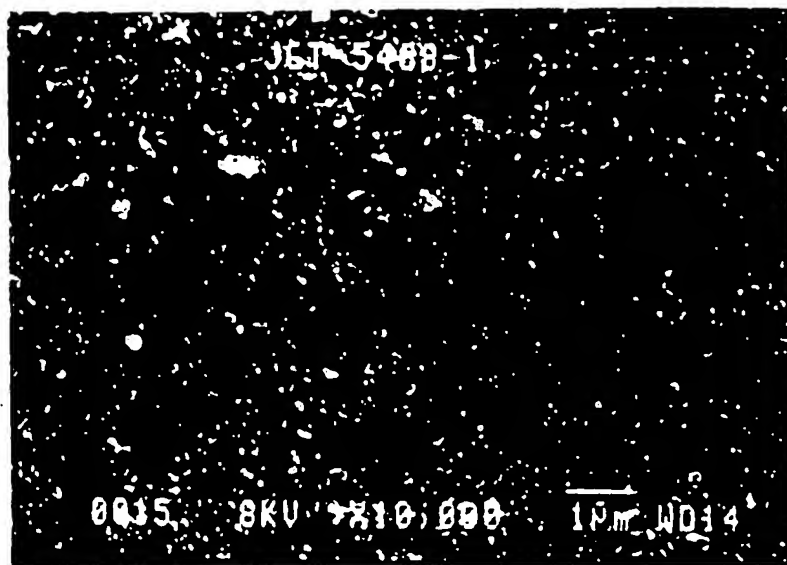


FIG. 2a

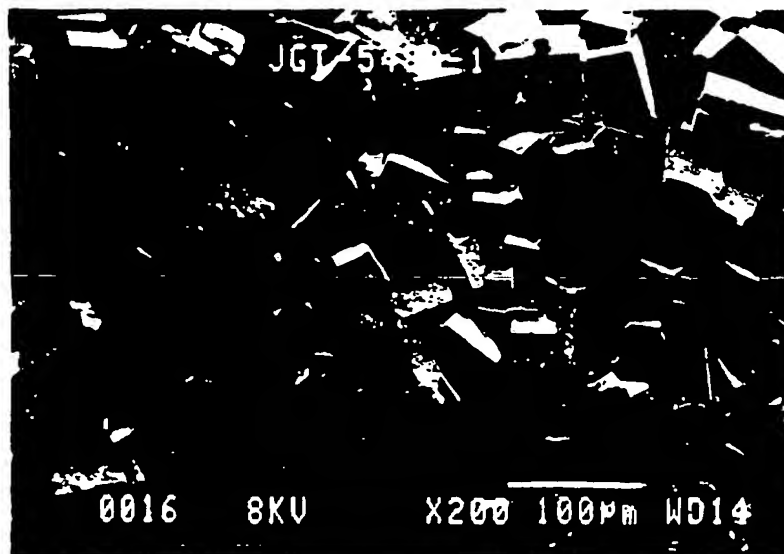


FIG. 2b

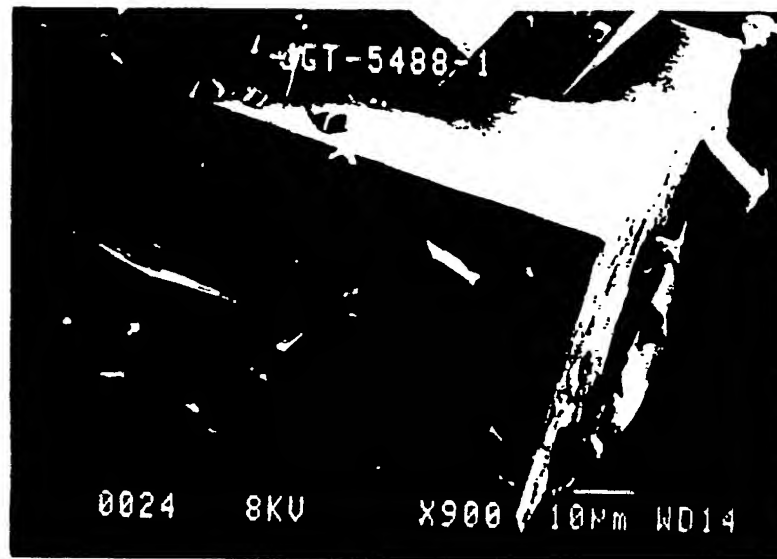


FIG. 2c

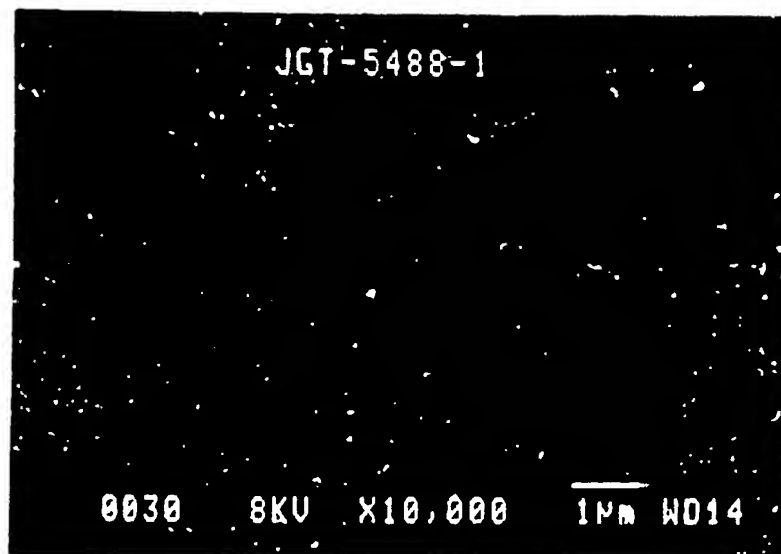
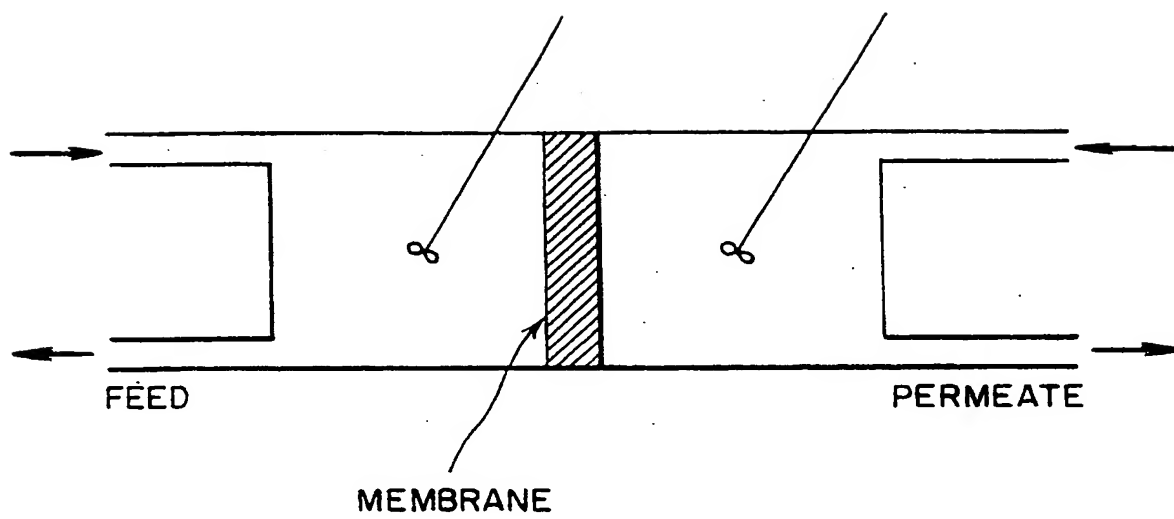


FIG. 2d



FIG. 3





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## EUROPEAN SEARCH REPORT

Application Number

EP 91 10 8734

### DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	DE-A-2 055 559 (E. FITZER) -----		B 01 D 71/02 B 01 J 29/06
A	US-A-2 924 630 (R.N. FLECK) -----		
A	PATENT ABSTRACTS OF JAPAN, vol. 10, no. 28 (C-326)[2085], 4th February 1986; & JP-A-60 179 134 (YUNION SHOWA K.K.) 13-09-1985 -----		
A	US-A-3 421 948 (J.E. WEBB) -----		
A	EP-A-0 135 069 (H. SUZUKI) -----		
A	US-A-3 650 687 (C.V. McDANIEL) -----		
A	US-A-3 356 450 (G. HEINZE) -----		
The present search report has been drawn up for all claims			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			B 01 D 71/00 B 01 D 39/00 B 01 J 29/00
Place of search		Date of completion of search	Examiner
The Hague		14 August 91	DEVISME F.R.
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